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EXPERIMENTAL DEMONSTRATION OF WAVELENGTH TUNING IN HIGH-GAIN HARMONIC GENERATION FREE ELECTRON LASER

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Abstract

Tunability is one of the key aspects of any laser system. In High-Gain Harmonic Generation Free Electron Laser (HGHG FEL) the seed laser determines the output wavelength. Conventional scheme of tunable HGHG FEL requires tunable seed laser. The alternative scheme [1] is based on compression of the electron bunch with energy-time correlation (chirped bunch) in the FEL dispersive section. The chirped energy modulation, induced by the seed laser with constant wavelength, compressed as the whole bunch undergoes compression. In this paper we discuss experimental verification of the proposed approach at the DUV FEL [2,3] and compare experimental results with analytical estimates.

INTRODUCTION

High-gain FELs have been proposed as high peak power light sources for the short-wavelength range [4,5]. Ultrashort and powerful radiation pulses from VUV to X-ray provide a unique possibility for studying fast processes in a large variety of scientific applications. Output radiation coherence, stability and tunability are important measures of the FEL performance.

For an initially prebunched beam, i.e. when the beam density contains a coherent bunching at the FEL resonant frequency, the FEL radiation output preserves full longitudinal coherence. In this case FEL acts as an amplifier of the external seed. Due to the nonlinearity of the FEL process, not only the fundamental harmonic can be amplified, but the higher harmonics too. This allows for frequency multiplication and generation of radiation in VUV and X-ray wavelength regions [6,7].

Seeding by an external source offers an opportunity to control the output pulse properties by controlling the shape of the input seed pulse. State-of-the-art conventional lasers are capable of providing ultra-short pulses with high peak power. Using the Harmonic Generation (HG) approach, one can shift and amplify the seed laser pulse in the short-wavelength region, preserving the flexible temporal format of the seed and generating short radiation output. Important benefits of seeded HG scheme are high stability, control of the central wavelength and small energy fluctuations due to stable input from the seed laser.

In HGHG scheme (Fig. 1), a coherent seed at a subharmonic wavelength of the desired output radiation interacts with the electron beam in an energy-modulating section. The energy modulation is then converted into spatial bunching as it traverses a dispersive section. In the second undulator (the radiator), which is tuned to a higher harmonic of the seed radiation, the microbunched electron beam first emits coherent radiation and then amplifies it exponentially until reaching saturation.

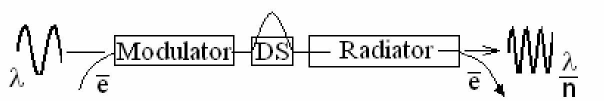

Fig.1: High Gain Harmonic Generation scheme

The seed laser determines the central wavelength of HGHG FEL. Therefore, as generally understood, to tune the wavelength of the seeded laser, the seed laser should be tunable. An alternative technique for the tunable HGHG FEL [1] utilizes a seed with fixed wavelength. The essence of this technique is in the compression of the chirped electron bunch in the HGHG dispersive section. Since the whole beam undergoes compression, the laser-induced modulation along the bunch also must be compressed with the same compression factor. Therefore prebunched electron beam enters the radiator with a new bunching wavelength. Changing the value of the energy chirp allows for a smooth tuning of the FEL output wavelength.

In this paper we present and discuss the experimental verification of this technique. In the experiment at the Deep Ultra Violet Free Electron Laser (DUV FEL, BNL) we have demonstrated tuning of the HGHG output around wavelength of 265 nm.

EXPERIMENT

In order to test new approach we performed an experiment at the DUV FEL (Fig. 2). The DUV FEL parameters are listed in Table 1.

For a phase offset $\Delta\varphi_{ch}$ the energy chirp h is given by the following expression [4]:

$$h = \frac{1}{E}\frac{\partial E}{\partial z} = -\frac{2\pi}{\lambda_{RF}}\frac{E_{ch}\sin(\Delta\phi_{ch})}{E_0 + E_{ch}\cos(\Delta\phi_{ch})}, \quad (1)$$

where E is the energy, z is longitudinal coordinate, λ_{RF} is RF wavelength, E_{ch} is amplitude of the chirping tank and E_0 is energy of the beam entering chirping tank.

The compression ratio for a chirped beam is:

$$C = \frac{\sigma_{out}}{\sigma_{in}} \approx 1 - R_{56}h, \quad (2)$$

The wavelength detuning due to compression is given by (3) [1].

$$\frac{\Delta\lambda}{\lambda} = \frac{\lambda_C - \lambda_0}{\lambda_0} = R_{56}\cdot h, \quad (3)$$

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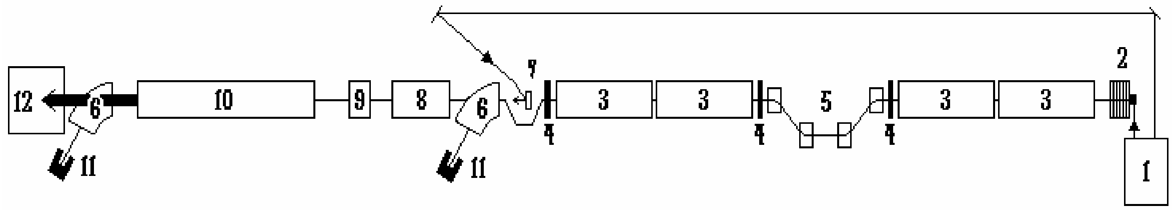

Fig. 2: The DUVFEL layout. 1 – gun and seed laser system, 2 – RF gun, 3 – linac tanks, 4 – focusing triplets, 5 – magnetic chicane, 6 – spectrometers dipoles, 7 – seed laser mirror, 8 – modulator, 9 – dispersive section, 10 – radiator, 11 – beam dumps, 12 – FEL radiation measurements area.

Beam energy, MeV	175
Seed laser wavelength, nm	800
Seed laser Raleigh range, m	2.4
Harmonic number	3
Radiator period, m	0.0389
Radiator length, m	10
Modulator length, m	0.8
Modulator period, m	0.08
Maximum R_{56} of DS, mm	-0.34
Bunch length (RMS), ps	0.5
HGHG pulse length (RMS), ps	0.5

Table 1: DUV FEL parameters

Using parameters from Table 1 together with expressions 1 and 3 we obtain the detuning of 0.37% for the phase offset of 33 degrees in the chirping tank. Changing sign of the chirp causes decompression of the energy modulation in the electron beam ($C>1$ in (2)) and, in turn, detuning towards longer wavelengths. Thus, for a symmetric chirp tuning range from +33° to -33° we calculate the DUV FEL tunability range of 0.74% or 2 nm around the nominal wavelength of 266 nm.

At the beginning of the experiment we minimized the projected energy spread in the beam canceling the energy chirp. The energy chirp has been measured by an energy spectrometer. The dispersion section current has been set to a maximum value, corresponding to the R_{56} value of -0.34 mm.

In the experiment we varied the phase of the last linac tank (tank 4 on Fig. 2), measuring HGHG spectrum for each value of the tank RF phase. The measured single-shot spectra are shown in Fig. 3. The nominal value of central wavelength for the beam without chirp has been measured as 265 nm. The overall wavelength tuning range is measured of about 1% (from 263.4 nm for -45° to 266.1 nm for 25° in RF phase).

Fig. 4 shows the dependence of the HGHG central wavelength versus energy chirp h. The first linear fit (solid line) is based on the expression 3, taking into account the R_{56} of the dispersion section. As it follows from the Figure, there is obvious disagreement between measured data and the fit. For a second linear fit (dashed line) we included dispersion in the radiator (R_{56}=-0.162 mm) into expression 3. In this case measurement is in a good agreement with calculation. This implies that the additional wavelength compression takes place in the radiator. The error bars in Fig. 4 correspond to the HGHG line width determined from the measured spectra.

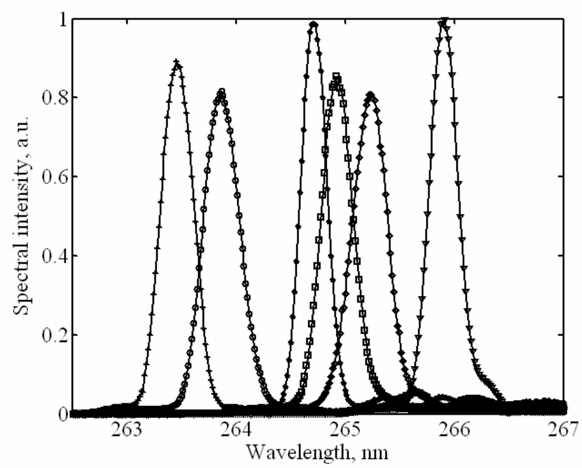

Fig. 3: Measured single-shot spectra for different values of energy chirp (phase offset from left to right: -45°, -30°, -10°, 0°, +10°, +25°).

At the DUV FEL the seed radiation is stretched out of approximately 100 fs long pulse with a bandwidth of 5.6 nm at 800 nm (Ti:Sapphire laser). The frequency-tripled seed pulse is 3 ps (RMS) long and contains wavelength chirp of 0.31 nm/ps at 266 nm. In Fig. 5 we compare the wavelength chirp in the DUV FEL seed laser with the energy chirp in the electron beam. For comparison we plot the chirped electron beam (bunch length of 1 ps, chirp is 11 m^{-1}) on the same figure, assuming that electron beam energy corresponds to the plot ordinate via expression for the FEL resonant wavelength. As follows from the plot, another way to achieve the wavelength detuning in our experiment would be by using the wavelength chirp in the seed laser pulse. In this case the electron bunch can be delayed (or expedited) in time and, therefore, would interact with a different local wavelength of the seed pulse. As the plot shows, measured tunability range of 1 % exceeds the seed laser bandwidth. Besides, in order to achieve the observed maximum detuning range, electron beam must be shifted by more than 3 ps (Fig. 5). We note that laser-to-beam synchronization has been kept constant during our experiment. Thus, observed wavelength detuning is due to the compression of the chirped electron bunch in the FEL dispersive section.

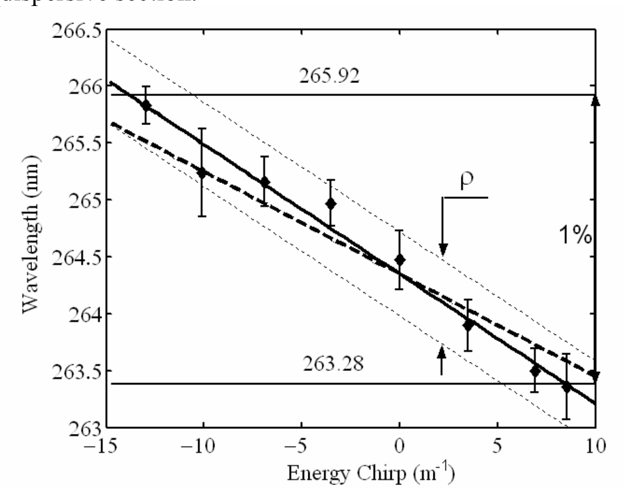

Fig. 4: Measured dependence of the HGHG central wavelength on the normalized energy chirp. Error bars represent measured single-shot HGHG linewidth. Dashed lines show FEL bandwidth, determined by the FEL parameter (ρ). Tunability range of one percent lies between horizontal lines. First fit (dashed line) is calculated based on the DS calibration. Second fit (solid line) takes into account dispersion in the radiator.

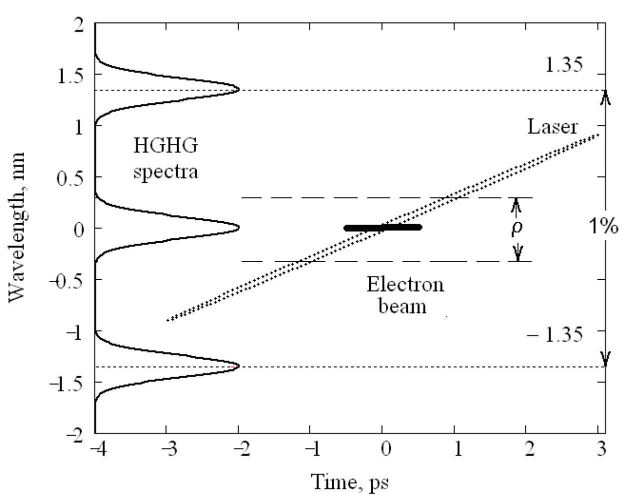

Fig. 5: Representation of the wavelength tuning range in wavelength (ordinate) – time (abscissa) coordinates. Tunability range of one percent lies between horizontal dotted lines. Measured tunability range exceeds the seed laser bandwidth.

CONCLUSION

In the experiment described in this paper we demonstrated control over HGHG FEL central wavelength. The precision of the positioning the central wavelength is, in general, a small fraction of the FEL bandwidth. This shows that we can tune the output photon energy with a high accuracy.

We performed wavelength tuning by changing only two parameters, linac section amplitude and phase. In contrast, when changing the seed laser wavelength, one has to change the seed laser set-up followed by optimization of the FEL set-up for new photon energy. The described method brings a simplification of the FEL tuning.

Demonstrated tuning range of one percent is below capabilities of modern lasers that can be used as a seed in HGHG FEL. In our experiment we were limited by the available dispersive section strength. Straightforward upgrade of the DUV FEL dispersive section is in progress. In this case we expect to increase the tuning range up to about 3 percent (it depends on the value of sliced energy spread that is not well known yet).

However, this is still not a limit. A special modification of the DUV FEL magnetic system [1] would increase the tunability range to ~20 %. The optimized HGHG scheme includes the secondary RF system located before and after FEL dispersive section. First RF section imparts a chirp in the beam, which, being compressed in DS, gets unchirped in the second RF section. Therefore chirp is provided only locally and, since it does not affect an FEL dynamics, can be made very large. In turn, this will provide a large wavelength tuning range.

Since the developed method can be used around any of HGHG harmonics (e.g. 4th, 5th, etc.), DUV FEL can be made tunable over a large wavelength range, having seed laser wavelength fixed.

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